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# MODELLING DAMAGE IN THIN-WALLED COMPOSITE STRUCTURES

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## 1 Abstract

A high-fidelity composite damage model is presented and applied to predict low-velocity impact damage, compression after impact (CAI) strength and crushing of thin-walled composite structures. The simulated results correlated well with experimental testing in terms of overall force-displacement response, damage morphologies and energy dissipation. The predictive power of this model makes it suitable for use as part of a virtual testing methodology, reducing the reliance on physical testing.

## 2 Introduction

Composite materials are finding increasing utilisation in a number of transportation industries concerned with making structures lighter to reduce environmental impact and improve efficiency. Nevertheless, composite structures are susceptible to damage from low-velocity impact events (e.g. accidental damage incurred during routine maintenance). Even with barely visible impact damage (BVID), CAI residual strength can be significantly reduced. Another major challenge in the development of land-based mass-transportation fibre-reinforced polymer composite vehicles, is ensuring a prescribed level of crashworthiness [1]. While the potential superior energy absorbing capacity of carbon-fibre composite structures is repeatedly demonstrated in Formula One racing [2], the design of a cost-effective crashworthy carbon-fibre reinforced polymer (CFRP) automotive passenger cabin has yet to be realised.

The accurate assessment of the effect of impact damage and the performance of composite structures under crush loading currently requires extensive experimental testing to meet certification requirements, which is costly and time-consuming. It is therefore essential that a reliable computational tool is developed to support the certification process and enhance the final design. The developed model fulfils this requirement by providing accurate and detailed modelling capability that does not require calibration of the input parameters.

## 3 Low-velocity Impact and CAI

The test case presented is based on experimental results in Ref [3]. The T700/M21 [0<sub>2</sub>,45<sub>2</sub>,90<sub>2</sub>,−45<sub>2</sub>]<sub>s</sub> composite laminate measured 100mm×150mm×4.16mm and was simply supported within a 'picture frame' with a 75mm×125mm effective test section. It was impacted with a hemispherical 16mm diameter, 2kg impactor, with an energy of 29.5J. The damage model allowed the various forms of intralaminar failure to be investigated as the impact event progressed. The impactor force vs. displacement history (Fig.1a) and residual strength prediction (Fig.1b) show very good agreement with experimental results. Fig.1c shows matrix cracking and delamination (modelled using cohesive contact laws) for each double-ply and interface, respectively. The delamination contours shown in Fig. 2c correlate well with results obtained from C-scans studies. CAI intralaminar damage plots for each ply pair and delaminations are shown in Fig.1d. During the CAI process, new delamination and intralaminar matrix damage developed from the impact-induced damage area. Fibre damage was primarily observed in the top and bottom plies. The predicted damage correlated well with experimental findings [3].

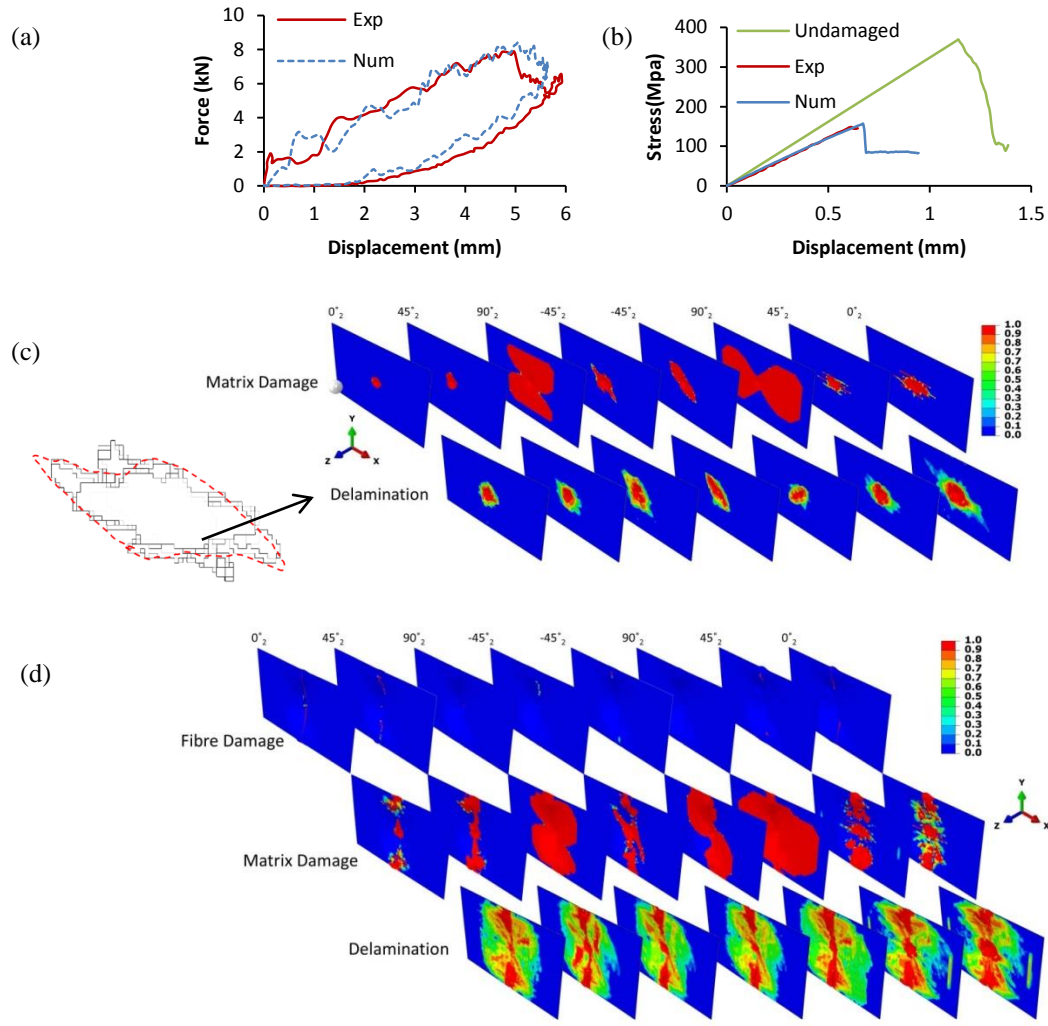
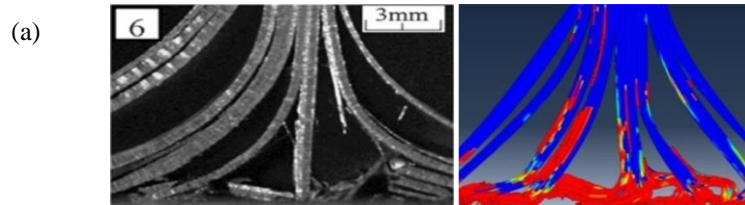


Fig 1: (a) Impact response; (b) CAI response; (c) Impact damage contours and (d) CAI damage contours.

#### 4 Crushing on wedges

Quasi-static crushing tests were performed by Israr et al. [4] using a hydraulic testing machine at a constant crosshead displacement rate of 6mm/min on T700/M21  $[(0^\circ/90^\circ)_4]_s$  laminates with a  $20^\circ$  chamfer angle. The global force-displacement response (Fig. 2a) further confirms the quantitative accuracy of the present damage model. The numerical oscillations are the result of element deletion laws invoked as part of the solution. The evolution of energy dissipated through various mechanisms during crushing is illustrated in Fig. 2b. The majority of energy was dissipated through intralaminar damage, followed by friction between the crushing platen and specimen, and delamination. The numerical results in Fig. 2c achieved excellent correlation with the experimental crushing morphologies. Internal debris was created and acted like a ‘wedge’ in driving delamination.



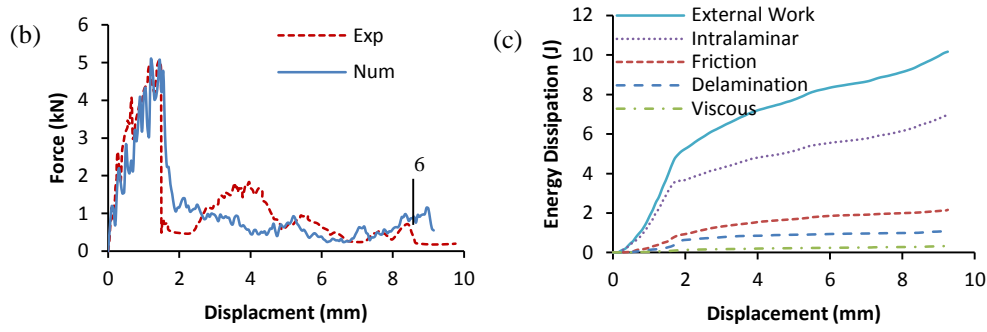


Fig 2: (a) Experimental morphologies [4] and numerical matrix damage contour; (b) force-displacement curve of crushing test on  $[(0^\circ/90^\circ)_4]_s$  specimen; (c) energy dissipation- displacement curves.

## 5 Strain rate dependence of crushing process

The application of energy absorbing composite structures, to attenuate crash forces, subjects these structures to high rates of loading. However, disagreement remains in the literature regarding the effect of increased loading rate on the crush response. An experimental investigation of the behaviour of a carbon-epoxy composite energy absorber under static and dynamic loading with a strain rate of up to  $100 \text{ s}^{-1}$  was completed to probe its rate sensitivity. Regression analysis of the specific energy absorption (SEA), the peak and steady-state crush force, and the crush efficiency shown in Fig 3 suggested that there was no significant strain rate sensitivity in the crashworthiness performance of this composite system across the range of strain rates examined.

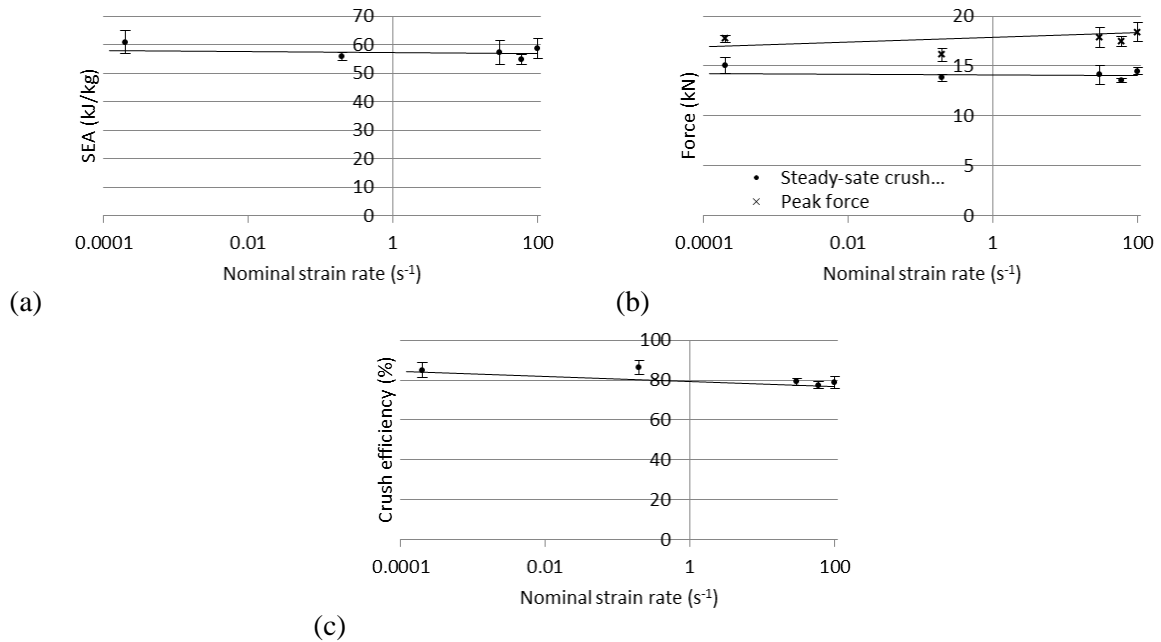


Fig 3: Averaged (a) SEA, (b) peak and steady-state forces and (c) crush efficiency over the tested strain rates.

The observed damage modes and deformation were also found to be invariant with increasing loading rate experienced by the specimen.

## 6 Crushing of thin walled structures

The different damage mechanisms and their interactions present significant challenges to the modelling of composite structures under crush loading. This study demonstrated the effectiveness of the proposed damage model in the prediction of crush damage behaviour for a range of different energy absorber designs. Four test cases were used and their geometries are shown in Fig 4. These test cases represent a range of different features encountered in the analysis of energy absorbing structures, including different triggers and cross-sectional geometries.

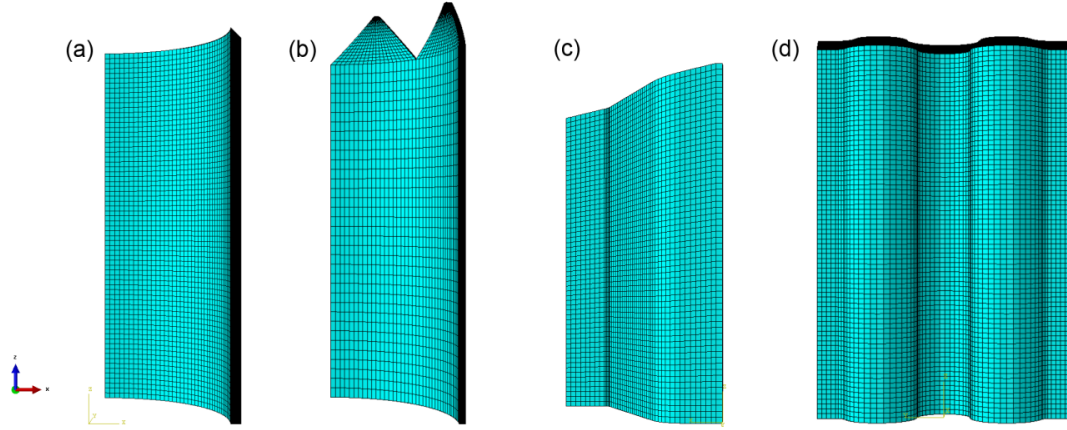


Fig 4: Mesh configuration for (a) chamfered cylinder [5], (b) tulip triggered cylinder, (c) hat section [6] and (d) corrugated web specimens [7].

Fig 5 shows comparisons between simulated and experimental force responses for each test case. It can be seen that the triggering and steady-state crush regions of the force responses were well captured by the damage model. In addition to the accurate reproduction of the crush force profile, the damage morphology and the structural deformation were also well captured. The splitting of the ply to form petals and the subsequent splaying of these petals were all observed in the simulations. Furthermore, the simulations were able to resolve the meso-scale damage mechanisms at the crush front, which also compared well with micrographs of the laminate cross-section.

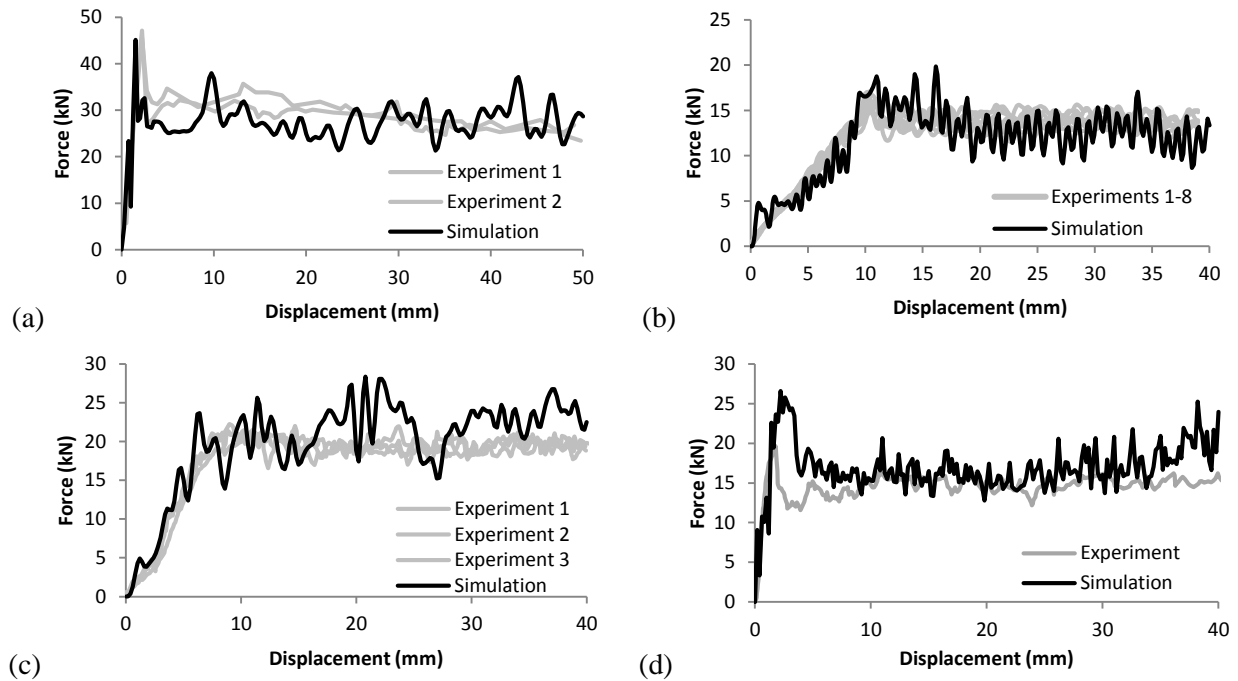


Fig 5: Comparison between simulated and experimental force responses for (a) chamfered cylinder[5], (b) tulip triggered cylinder, (c) hat section [6] and (d) corrugated web specimens [7].

These results confirm that this damage model has the capacity to simulate composite structures under crush loading with excellent results. In addition, these results were obtained using only the geometry and measured material properties of the structure without the need of ‘calibration’. Thus, the utility of the model for use in virtual testing to reducing physical testing requirement is evident.

## 7 Conclusion

A comprehensive composite damage model has been developed to meet the demands of virtual testing. It was shown that this model is applicable to a range of different structures and different load cases. Comparison of the numerical results against experimental data demonstrated the predictive capability of this model for assessing impact damage, compression after impact strength as well as the crushing performance of thin-walled composite structures. In all of the test cases examined, the model successfully reproduced not only the force response, but also the resulting damage morphology and the structural deformation. These results were obtained without the need for calibration of input parameters, demonstrating the predictive capability of the model. This establishes the basis on which this model can be used for virtual testing.

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